DIE BIBLIOTHEK DER TECHNIK 314

Polymers for Electrical Insulation

Coatings and casting materials
for the electrical industry

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important information with respect to the suitability of a system for a specific end use.

Tests to determine the dielectric properties of the impregnating resin include insulation class and comparative tracking index, as well as methods to determine the breakdown voltage and volume resistance at elevated temperatures or after water storage.

Casting and potting compounds

Background

For very high requirements impregnating an electrical part is often not sufficient. Additionally, predefined specific shapes cannot be realized by means of impregnation, because the polymer covers the electrical device evenly. For these requirements, casting and potting form an alternative that allows the design and construction of electrical devices and components that could not function otherwise. Furthermore, it is an economic alternative for small parts.

Potting refers to a technique where a device (e.g. a transformer) is placed within a vessel while a liquid compound is poured into the vessel from the top, covering the device and fully encasing it. The vessel becomes part of the finished unit when the polymer is fully cured (Fig. 27). The casting method uses the
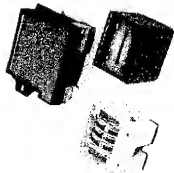
Alternative

Fig. 27:
Small transformers
that have been
protected by potting

Difference

same concepts as in potting, but the vessel does not become part of the finished unit and is removed after the resin has hardened (Fig. 28). In practice, both terms are often used loosely and interchangeably.

Much like the impregnation process described in the previous chapter, potting and casting unpart additional stability, function to reduce noise, consolidate a device, protect against en-
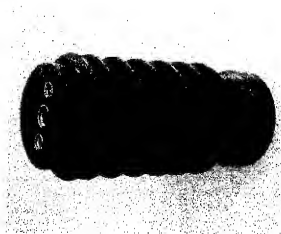

Fig. 28:
Casting was used to manufacture this insulator rod.

vironmental influences, insulate and increase the operating temperature of electric and electronic parts. However, there are significant differences: in the case of impregnating resins, the thickness of the layer that can be applied depends on how much material adheres to the electric part and how much drips off. This limitation does not apply to casting and potting, where the thickness of the layer is only limited

by the size of the vessel. Since the thermosetting polymer encases the electric or electronic part a very high degree of filling is achieved. This in turn leads to very good heat dissipation, because polymeric materials conduct heat much better than air (the heat conductivity of air is 0.03 Watt m⁻¹ K⁻¹, for a pure polymer it is 0.3 Watt m⁻¹ K⁻¹, and for a filled polymer the heat conductivity can be as high as 1 Watt m⁻¹ K⁻¹). The price for these advantages is a much higher resin consumption compared to impregnation.

In the 1950s when the major use of potting and casting was first developed, epoxy resins were the workhorse of these types of insulating materials. More complex and higher performance devices as well as new developments in application techniques such as highly automated lines for vacuum casting and injection led to increasingly diverse material demands which required the availability of a range of different chemistries. To this end, polyurethanes, polyesters, phenolic resins, silicones and acrylics, which all show distinct properties profiles, have also been applied in the meantime.

High filling degree

Wide range of different chemistries

Market for casting and potting compounds

The market can be broadly split into three sectors: heavy electric, light electric and electronics.

The heavy electric sector comprises larger devices that are often operated at medium to high voltages. Transformers used for power distribution (Fig. 29) and instruments belong to this sector. Switchgear, motors and generators are also considered part of this application field.

The light electric sector forms the most important part of this market. It includes essential
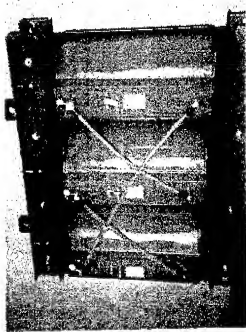
Heavy and ...

... light electric sector

parts for everyday consumer electrical goods. The applications cover the full range of voltages from low to high voltages, examples being a variety of smaller transformer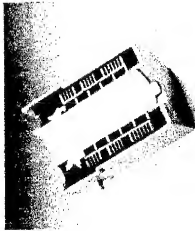s used in printed circuit boards (PCB), lighting, home appliances, automotive uses and more. Smaller generators and motors such as those found in power tools, submersible pumps home appliances and some automotive applications are further examples (Fig. 30). Other parts within circuits such as capacitors and power semiconductors are also included.

Electronic protection considers a wide variety of electronically controlled components. In this area, potting compounds can be electrically active or passive. This means that in some instances, the thermosetting material actively contributes to the electrical protection of a component (active) or in others is solely for the integrity and environmental protection (passively) of a component. Figure 31 shows an example for potting in an electronic application.

Epoxy resins

Chemistry

Epoxy resins are the most widely utilized resins for potting and casting electrical devices. They are characterized by a three-men-

Active or passive

Fig. 31:
Potting of an electronic component

Fig. 29:
Heavy-duty transformer

Fig. 30:
Fly-back transformer for cathode monitor

Three-membered ring

bered ring known as the epoxy, epoxide or oxirane group. To enable cross-linking, the epoxides must be at least bi-functional. The most typical and economical epoxide building block for potting and casting is the diglycidylether of bisphenol-A (DGEBA). An alternative to DGEBA with lower viscosity constitute bisphenol F-type resins. Their lower viscosity reduces the need for diluents, which improves thermal and mechanical properties. The epoxy resin is cross-linked to a three-dimensional insoluble and infusible network by the reaction with a curing agent (hardener). The choice of the hardener depends on factors such as processing methods, curing conditions and which final physical and chemical properties are desired. For casting and potting, the two major types of hardeners in use are amines and anhydrides. Amines can be used at ambient temperature and above, anhydrides require elevated temperatures.

Amines and anhydrides

Amine cure

Reactions of amine-cured epoxies are based on the oxirane ring being opened by the amine nitrogen. Figure 32 depicts the amine cure of an epoxy resin: an amine atom attacks the epoxy carbon and opens the epoxide. In a second
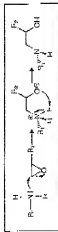
Fig. 32:
Amine cure of an epoxy resin

step, the hydroxyl-anion abstracts hydrogen from the positively charged nitrogen to arrive at an uncharged final structure.

Initially, the predominant reaction of the primary amine groups (two hydrogens attached to the amine = RNH_2), which are more reactive than secondary amine groups (one hydro-

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gen attached to the amine = R_2NH), leads to the build-up of roughly linear segments with limited molecular weight. As the reaction continues, the secondary amine groups that were part of the original hardener or that have been formed by the reaction of a primary amine with an epoxide ring (see Fig. 32) also react. With the di- and polyamines that are used for potting and casting, this cross-linking leads to the formation of a three-dimensional network and rapidly increasing viscosity. Figure 33
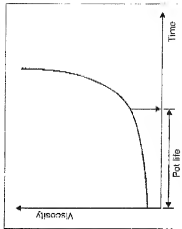

Fig. 31.
Viscosity change during the curing process

shows the viscosity as a function of time. Once the viscosity starts to increase dramatically, the end of the usable period has been reached. This viscosity increase leads to a finite useable processing time for the material. This time period is known as the pot life. The starting viscosity together with the pot life determines the processing parameters of a system.

For the optimum property profile, full cross-linking is required so that a true stoichiometric ratio amine to epoxy should be maintained and heat is applied as a post cure. Amine curatives can be subdivided into aliphatic, cycloaliphatic, fatty-acid-modified

Pot life

Amine type	Cure rate	Pot life (at 25°C)	Viscosity (mPas)	Resistance of polymer against		
				Chemicals	Solvents	Heat
Aliphatic amines	Very fast	Very short	5–10	***	***	**
Cyclo-aliphatic amines	Fast	Short	50–500	****	***	**
Fatty-acid-modified amines	Moderate/ Slow	Long	4000–solid	**	**	**
Aromatic amines	Heat required	(near solid)	2000–solid	****	***	****

Tab. 3:
Comparison of different types of amine hardeners

**** = excellent, *** = very good, ** = good, * = acceptable, · = poor

and aromatic amines, and also include hetero-cyclic nitrogen compounds such as imidazoles. Table 3 compares the properties of these hardener types.

Anhydride cure
The reaction of anhydrides with epoxides must be catalysed to proceed at acceptable speed even at elevated temperatures. Catalysis can
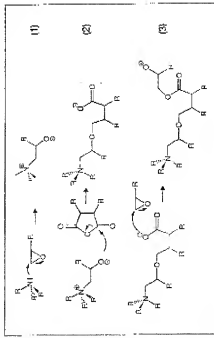
Fig. 34:
Reaction scheme for the amine-catalysed formation of polyester from acid and anhydride and epoxide

be tertiary amines or Lewis acids. Figure 34 depicts a typical amine-catalysed reaction sequence. Ring-opening of the epoxide by the tertiary amine initiates the reaction sequence (1). The hydroxyl anion that was formed by the ring-opening attacks the anhydride. This leads to the formation of the half-ester of a dicarboxylic acid (2). The carboxyl-oxygen anion opens the ring of another epoxide group (3). The oxygen anion thus formed propagates the reaction by attacking an anhydride as shown in step 2. The final result of this condensation reaction is a polyester.

The oxygen anion that is formed when the epoxide ring is opened (Fig. 34, steps 1 and 3) can, instead of opening the ring of a carboxylic acid anhydride to form the half-ester (Fig. 34; step 2), also attack another epoxide ring. In this case, an

Amine-catalysed formation of polyester

Fig. 35:
Polyester formation

Formation of an ether linkage

ether linkage is formed: a hydroxide anion formed by the ring-opening of an epoxy group attacks another epoxide. R¹ can be an amine catalyst or a polymer chain consisting of polyester and polyether sections. In practice, two competing reactions take place: the esterification as the result of the reaction of the epoxide with the acid anhydride and the ether formation due to homo-polymerization of the epoxide.

Esterification gives the most desirable mechanical properties. Esterification gives the best chemical and thermal resistance. The competing reactions will be influenced by reaction temperature, water content, concentration of hydroxyls, and the catalyst. Desirable stoichiometries of anhydride to epoxy groups can range from 0.4 to 1.2, dependent upon the desired final properties. It has

been proposed that optimum properties are obtained at a ratio of 1:1 for base-catalysed 0.55:1 for acid-catalysed and 0.85:1 for non-catalysed systems. However, for a particular application this ratio must be determined empirically. Usually, acid anhydrides are crystalline substances. In order to be able to properly mix the resin with the anhydride, it is necessary that the acid anhydride is a liquid. This is possible by using isomeric mixtures of alkyd-substituted anhydrides. The most commonly used acids for potting and casting are methylhexahydrophthalic anhydride, methyltetrahydrophthalic anhydride, dodecenyl succinic anhydride, nadic anhydride, and methylnadic anhydride.

Additional components

In order to adjust viscosity and other properties further, a number of mono- and di-functional reactive diluents such as butyl glycidyl ether, 1,4-butanediol diglycidyl ether, and cresyl glycidyl ether can also be added. The amount of non-reactive diluents or plasticizers such as phthalates, mixtures of hydrogenated aromatics or propylene glycols is generally limited in order to avoid the degradation of thermal properties.

Thermal conductivity, cost, thermal expansion coefficient and exothermic behavior on cure can be improved by inorganic fillers. They can also impart self-extinguishing properties to the system. Specialized fillers can be added for viscosity control.

Advantages and disadvantages

Epoxies provide strength, resistance to thermal cycling, resistance to thermal and thermal stability as well as good wetting, adhesion and compatibility with other resin species. A disadvantage of epoxies arises from their high modulus and low elongation to break (see Fig. 39, p. 62), resulting in low thermal shock

Margin labels:
Liquid acid anhydride

Reactive diluents and …

… inorganic fillers

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resistance and brittleness, which needs to be kept in mind when the system is formulated.

Polyurethane resins

Polyurethane potting is a popular option for circuits and sensors in the automotive sector. A second major application field is the sealing and protection of printed circuits.

Chemistry

Figure 36 shows that the polyurethane group is the product of an addition of a hydroxyl group (in blue) to the carbonyl carbon (carbonyl group in red) of the isocyanate group (-NCO). In order to obtain a polymeric structure, di- or multi-functional isocyanates and di- or polyols are used. The urethane formation advances readily at room temperature.

The properties of polyurethanes are linked to their two- or poly-phase morphology: long flexible segments are followed by much
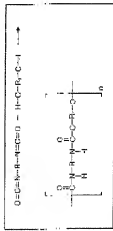

shorter rigid units which are chemically and hydrogen-bonded (Fig. 37). The rigid blocks are formed by the isocyanate and the flexible blocks by the polyol segments The polymer properties are closely linked to segmented flexibility, inner chain forces, cross-linking and chain entanglement. They can be varied by a modification of the diisocyanate and the polyol.

Margin labels:
Use of diisocyanates and diols

Fig. 36
Formation of a linear polyurethane from a diisocyanate and a diol
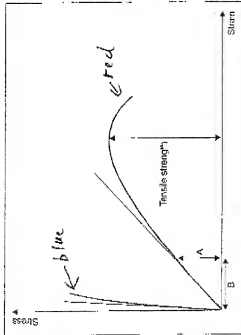
Fig. 39:
Stress-strain curve
for a brittle polymer
(blue) and an elastic
polymer (red). The
tensile strength gives
information about
the maximum stress
the material can
withstand before
breaking. The initial
slope of the curve
(A/B) is the electric
modulus.

Chemical tests such as the resistance of the polymer to various solvents, chemicals and water provide information about the suitability of the potting or casting material for certain environments. These tests are often combined with the testing of the electrical properties, which are measured before and after prolonged exposure to a certain environment.

The most important electrical tests are the volume resistivity both before and after immersion in water and at various temperatures, the permeability loss factor as a function of temperature and frequency, the permeability and the breakdown voltage at different temperatures. Finally, the tracking index permits important conclusions to be made about the behavior of the material after a sparkover has occurred.

International and national standards

To ensure that users can compare materials from different manufacturers, the International Electrotechnical Commission (IEC), which is made up of the national organizations such as the Deutsche Institut für Normung (DIN), the British Standards Institute (BSI), Japan Electrical Measuring Instruments Manufacturers Association (JEMIMA) and the American National Standards Institute (ANSI) develops standards for electrical insulation products. Other important organizations are the Institute of Electrical and Electronic Engineers (IEEE), the American Society for Testing and Materials International (ASTM International), and the US-based National Electrical Manufacturers Association (NEMA).

In order to verify that an electrical insulation system meets a certain norm or standard the supplier of the material and/or the manufacturer of the finished part can employ a certified testing lab to validate a certain quality standard. The Underwriters Laboratory's (UL) certifications, which originally were established to meet the needs of the US insurance industry, have established themselves as a worldwide standard for electrical insulation.

The following norms are a selection of the most important international standards relevant for electrical insulation. A large number of more specific norms are quoted within these norms which describe details on how to test. The norms quoted in the following text usually exist in an IEC/ISO version, in nationalized versions, as well as in an ASTM version. Due to space restrictions, the focus is on the IEC and ISO norms.

Certified testing